Editors' Suggestion

Measurements of Z-Boson Pair Entanglement in Decays of Higgs Bosons at the ATLAS Experiment

G. Aad *et al.*[*]
(ATLAS Collaboration)

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Entanglement is a key property of quantum systems. In this Letter the first measurements of quantum entanglement between spins in pairs of Z bosons are reported, using proton-proton collision data from the Large Hadron Collider (LHC) at center-of-mass energies of 13 and 13.6 TeV, recorded with the ATLAS detector. Measurements of angular observables sensitive to ZZ^* spin-density-matrix elements in the $H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$ process yield coefficients $C_{2,1,2,-1} = -0.71 \pm 0.45$ and $C_{2,2,2,-2} = 0.08 \pm 0.44$, consistent with their Standard Model predictions. A complementary hypothesis test using the full angular distribution, and relying on several Standard Model assumptions in the decays, provides substantially higher sensitivity to quantum correlations and disfavors the separable-state hypothesis at a significance of 4.7 standard deviations (expected 4.9σ) relative to the entangled Standard Model hypothesis. These results provide strong evidence of quantum entanglement between massive bosons (spin qutrits) at the electroweak scale.

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Quantum entanglement is one of the fundamental features of quantum mechanics [1–3], lying at the heart of quantum information science and quantum field theory [4–8]. In quantum mechanics, an entangled system cannot be described as a product of its subsystems. (More precisely the condition for a density matrix ρ to be entangled is that it is not possible to express it as a convex sum of tensor products $\rho = \sum_i p_i \rho_A \otimes \rho_B$ of the density matrices ρ_A and ρ_B of the subsystems A and B for $p_i \geq 0$ and $\sum_i p_i = 1$.) Its joint state exhibits correlations that cannot be reproduced by any nonentangled quantum model.

In recent years, collider-based studies have been proposed, which would probe entanglement at the highest experimentally accessible energy scales [9–13], building on techniques first developed for optical and atomic systems [14–17]. Entanglement has also been observed in flavor in systems of K mesons [18] and B mesons [19]. Analyses at CERN's Large Hadron Collider (LHC) have demonstrated the feasibility of tests of spin entanglement in top-quark pair production, culminating in the recent observation by the ATLAS and CMS Collaborations [20–22]. As well as being intrinsically of interest, such measurements offer sensitivity to possible new particles and fields, with quantum tomography of the polarization density matrix providing a systematic basis for constraining anomalous couplings [23–25] and, more broadly, for probing deviations from Standard Model dynamics [26]. Recent reviews of the broader collider program in quantum information measurements can be found in Refs. [27,28]. Extending such measurements to systems with bosonic particles enables tests of quantum correlations among massive vector fields [11–13], and provides a probe of the electroweak symmetry-breaking sector responsible for generating the masses of elementary particles [29–33].

The decay of the Higgs boson into a pair of Z bosons provides an ideal laboratory for such studies. In the Standard Model, the Higgs boson is a scalar particle and is even under the charge-conjugation (C) and the parity (P) transformations ($J^{PC} = 0^{++}$). The Z is a massive spin-1 boson with three possible spin states, called spin qutrit, and so each Z spin state can be labeled $|+\rangle$, $|0\rangle$, or $|-\rangle$ according to its helicity. Since the mass of the Higgs boson is smaller than twice that of the Z boson, the $H \to ZZ$ decay involves at least one off-shell (virtual) Z boson denoted Z^*. Virtual Z^* bosons decaying into highly relativistic leptons are also spin qutrits, spanning the same triplet of helicity states. The Higgs boson decay into four charged leptons via two spin-1 bosons, $H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$, therefore produces a system that can be described by three dominant Z-pair helicity amplitudes: $|+-\rangle$, $|00\rangle$, and $|-+\rangle$. The corresponding two-boson quantum spin state, $|ZZ\rangle = a|+-\rangle + b|00\rangle + c|-+\rangle$, is expected to be nonseparable due to the coherent superposition of helicity components. The presence of off-diagonal elements in the associated 9×9 spin-density

[*]Full author list given at the end of the Letter.

matrix (SDM) therefore constitutes a direct signature of entanglement between the spins of the two Z bosons [11].

This Letter presents the first measurement of quantum entanglement between massive vector bosons at the electroweak scale. Distinctive features make such measurements at high-energy colliders fundamentally different from those in atomic or photonic systems. First, the LHC probes energies at the electroweak scale, allowing tests of entanglement for short-lived, massive particles. Second, in the context of the Standard Model of particle physics, collider experiments can reconstruct the spins of virtual, off-shell bosons through angular correlations of their decay leptons because the chiral nature of weak decay allows one to relate these angular distributions to the spin state of the parent particles. A further advantage of the Higgs decay process studied in this Letter is that it offers a clean, fully reconstructible final state with minimal background.

This Letter presents the analysis of Higgs-boson decays into four charged leptons recorded with the ATLAS detector [34] at the LHC. It reports measurements of entanglement-sensitive angular distributions of ZZ^* decay products and the corresponding average values that are related to two entanglement-sensitive SDM coefficients $C_{2,1,2,-1}$ and $C_{2,2,2,-2}$ [11]. The measured average values are interpreted within the Peres-Horodecki criterion [35,36] for separability. The measured angular distributions are also employed to test the hypothesis of an entangled ZZ^* system as predicted by the Standard Model against a null hypothesis of a nonentangled system in which both Z bosons are longitudinally polarized ($|00\rangle$). For a CP-even spin-0 Higgs boson, as predicted by the Standard Model, this purely longitudinally polarized system is the only configuration that can yield a nonentangled state [37]. Both approaches allow for a direct experimental test of quantum entanglement of spins in a fundamental bosonic interaction. The first approach yields a direct measure of entanglement via the spin-density matrix elements; however the spread of the angular distribution diminishes the statistical accuracy that can be achieved using existing event samples. The second approach achieves greater sensitivity by using the full distribution, with some increased model dependence, as it relies on a comparison between two specific hypotheses.

The analysis rests on several assumptions, each supported by both Standard Model expectations and prior experimental results. First, the pairs of Z bosons produced in Higgs-boson decays are assumed to form a scalar state, consistent with existing measurements of the Higgs boson spin and CP [38,39]. Second, the angular distributions of the leptons arising from each helicity state of the $Z^{(*)}$ bosons are assumed to follow the Standard Model predictions, enabling the measurement of its spin from those distributions. Approximate conservation of CP excludes individual transverse Z-boson polarizations. Higher-order corrections in electroweak perturbation theory, including those from processes without ZZ^* intermediate states, are predicted to affect leptonic angular distributions and can lead to large biases in measurements of some elements of the SDM [40,41]. Dedicated observables are therefore selected that probe particular entanglement-sensitive elements of the matrix that have small ($< 2\%$) higher-order corrections [42], these corrections being treated as systematic uncertainties. Finally, the angular distributions of the four-lepton background processes are assumed to be well-described by the Standard Model, an assumption that is then verified with dedicated signal-free control data. Together, these assumptions (the interpretation of collider data in non-Quantum Mechanical theories via Bell's inequality has been discussed in Ref. [43]; the results presented in this Letter are not concerned with probing alternative theories to quantum mechanics via Bell inequalities, but rather in establishing the quantum nonseparability of the Z bosons spin states in $H \to ZZ^*$ decays) enable the interpretation of the observed angular correlations in $H \to ZZ^* \to 4\ell$ decays in terms of quantum spin entanglement.

The analysis uses proton-proton collision data collected with the ATLAS detector [34] at the LHC, employing the full Run 2 dataset (2015–2018) at a center-of-mass energy of 13 TeV and partial Run 3 (2022–2024) data at 13.6 TeV, corresponding to integrated luminosities of 140 fb^{-1} and 164 fb^{-1}, respectively. ATLAS is a multipurpose cylindrical particle detector composed of several subdetectors with a forward-backward symmetric cylindrical geometry and a solid-angle coverage of almost 4π. It is used to record particles produced in LHC collisions through a combination of particle position and energy measurements. It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS). The MS surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each providing a field integral of between 2.0 Tm and 6.0 Tm across the detector.

Signal and background processes are modeled using Monte Carlo event generators with detailed simulation of the detector response based on Geant4 [44]. All samples are normalized to the most precise theoretical cross-sections currently available. The simulated events are weighted to correct for differences between simulated and measured lepton trigger, reconstruction, identification, and isolation performance. Background simulations are validated in dedicated signal-free control regions.

The simulated signal corresponds to Standard Model Higgs boson production via the dominant gluon-gluon fusion process (Fig. 1), vector-boson fusion, and production in association with a W or a Z boson or with one or more third-generation quarks, followed by decay into four charged leptons. This signal is hereafter denoted "QE $H \to ZZ^*$." A null hypothesis corresponding to a nonentangled (separable) quantum system with both Z bosons

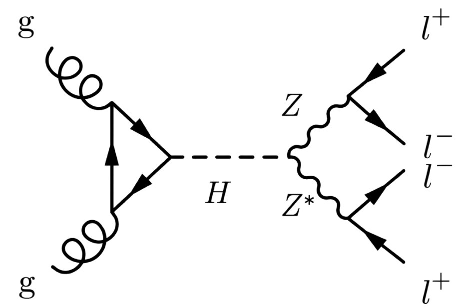


FIG. 1. Example of a leading-order Feynman diagram of the dominant Higgs-boson production process via gluon-gluon fusion through a fermion loop and its decay process into two leptonically decaying Z bosons, $pp \to H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$. The superscript (*) refers to a particle that is off its mass shell.

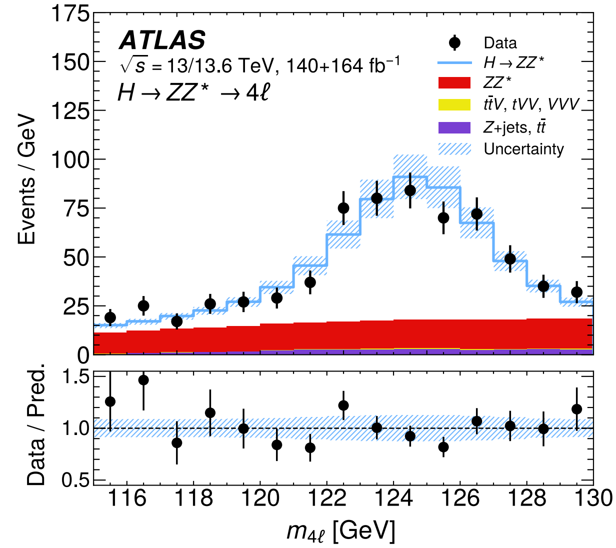


FIG. 2. Observed (full circles) and the expected (histograms) four-lepton invariant mass distribution around the observed Higgs boson resonance. The expectation shows the contributions from $H \to ZZ^* \to 4\ell$ and from various background processes as described in the text. The uncertainty bar on data points is Poisson errors, and the uncertainty band includes statistical and systematic contributions added in quadrature.

longitudinally polarized ($|00\rangle$) is simulated and denoted "Non-QE $H \to ZZ^*$.". Backgrounds are dominated by nonresonant diboson production (denoted $ZZ^{(*)}$), with smaller contributions from top quarks (or antiquarks) produced in association with Z bosons ($ttV + tVV$) and triboson production (VVV) where V is a $W^\pm$ or Z boson. A subdominant "reducible" background arises from $Z +$ jets events and $t\bar{t}$ when events with fewer than four leptons from the interaction point enter the analysis. Details of the signal and background event simulation may be found in Appendix A of End Matter.

The analysis is based on the correlations in angular distributions of charged leptons originating from pairs of $Z^{(*)}$ bosons produced in the decays of Higgs bosons. Selection criteria are employed following an established ATLAS $H \to ZZ^* \to 4\ell$ event selection strategy [45]. Events are selected using single- and dilepton triggers [46,47] for electrons and muons, which together have an efficiency of about 98% for selecting signal events in the $H \to ZZ^* \to 4\ell$ final state. Events are required to contain at least four isolated charged leptons (e or μ). Electrons are reconstructed from electromagnetic clusters matched to particle tracks within the ID [48] and must have transverse momentum $p_T > 7$ GeV and pseudorapidity $|\eta| < 2.47$ (with the region $1.37 < |\eta| < 1.52$ excluded). Muon candidates are reconstructed using tracks in the MS which within $|\eta| < 2.5$ are matched to ID tracks, and with additional recovery in $|\eta| < 0.1$ using ID tracks matched to MS segments or energy deposits in the calorimeters compatible with a minimum-ionizing particle [49]. Muons are required to have transverse momentum $p_T > 5$ GeV and $|\eta| < 2.7(2.5)$ for Run 2 (Run 3) data. Isolation criteria are imposed on the leptons and they are required to originate from a common vertex point. The three highest-p_T leptons must have transverse momenta exceeding 20, 15, and 10 GeV, respectively.

The analysis is performed for the $4e$, 4μ, and $2e2\mu$ channels. The candidate Higgs boson in each event is reconstructed from two pairs of same-flavor opposite-charge leptons (e^+e^- or $\mu^+\mu^-$). From all valid pairings of the candidate leptons, the lepton pair with the invariant mass closest to the nominal value of the Z boson mass [50] is denoted Z_1, while the second closest is denoted Z_2. Any additional leptons not entering those pairings play no role in the analysis. The invariant mass of these two candidates must satisfy 50 GeV $< m_{Z_1} <$ 106 GeV and 12 GeV $< m_{Z_2} <$ 115 GeV, and the invariant mass of four leptons must be close to the Higgs boson mass [50,51]: 115 GeV $< m_{4\ell} <$ 130 GeV. The observed and expected $m_{4\ell}$ distributions from combined Run 2 and Run 3 data samples are shown in Fig. 2.

For each selected event, the lepton emission directions are defined relative to separate coordinate systems constructed in the rest frame of each parent Z boson [52] as illustrated in Fig. 3. The z axis in both is aligned with the momentum direction of the Z_1 boson in the Higgs-boson rest frame. The spin analyzers are given by the polar and azimuthal angles (θ, ϕ) of each negatively charged lepton in its respective parent's rest frame. The relevant off-diagonal entanglement-sensitive parameters of the SDM are then obtained from products of spherical harmonics $Y_L^M(\theta, \phi)$ from event-by-event real-valued estimators [11],

$$c_{2M_1 2M_2} = 40\pi \Re(Y_2^{M_1}(\theta_1, \phi_1) \times Y_2^{M_2}(\theta_2, \phi_2)),$$

where the integers $M_1 = -M_2$ are either 1 or 2. The values of the SDM coefficients $C_{2M_1 2M_2} = \langle c_{2M_1 2M_2} \rangle$ are obtained from the averages of these event-by-event estimators over

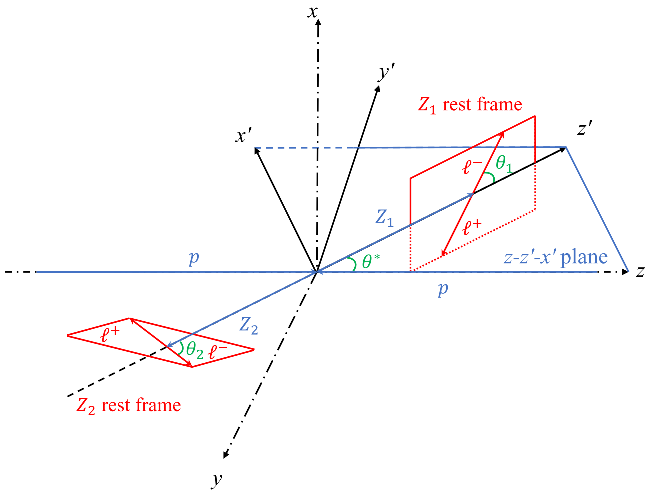
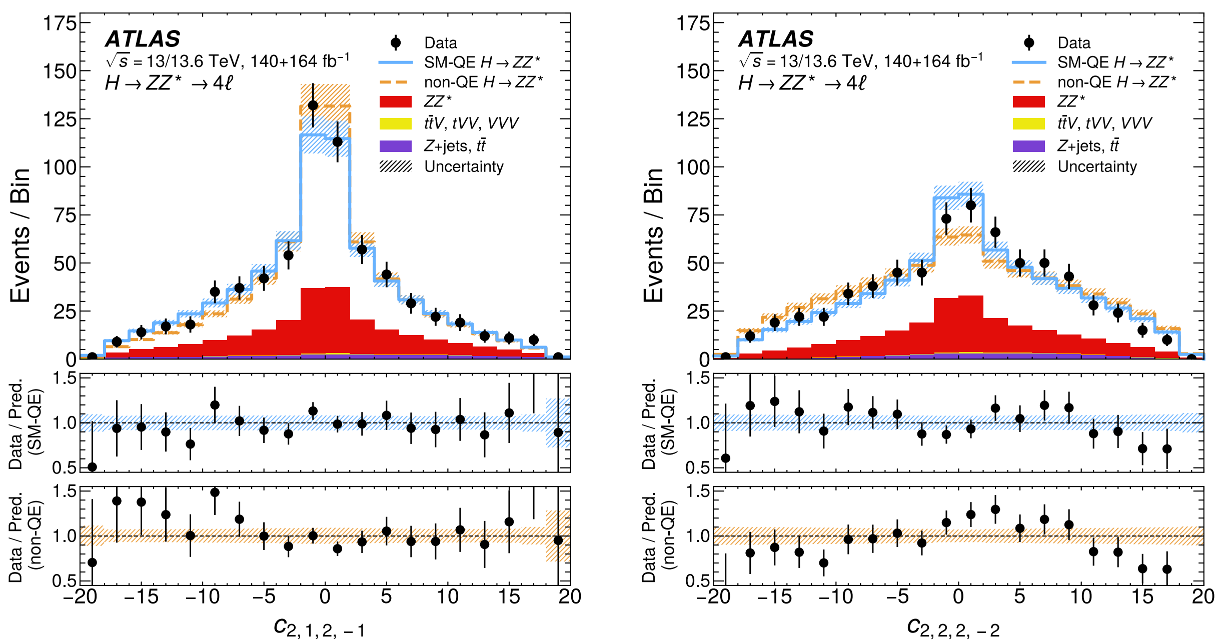


FIG. 3. Illustration of the decay angle definitions in the $pp \to H \to ZZ^* \to 4\ell$ process. The azimuthal angles ϕ_1 and ϕ_2 are not shown in the figure and are defined in the conventional manner for right-handed coordinate systems. The unprimed frame is the laboratory frame with the z axis along the beam direction. The primed frame is that in which the polarization of Z bosons is defined.

events within the kinematic region defined by the dilepton and four-lepton mass requirements listed in the previous paragraph. During the calculation of the average values corrections are applied for the effects of background processes, detector acceptance, reconstruction effects, and higher-order electroweak corrections, as described in Appendix B of End Matter. In the same-flavor decay channels ($4e$, 4μ), quantum interference arising from multiple indistinguishable assignments of identical leptons to the intermediate Z bosons leads to modifications of the SDM elements at the level of roughly 10% [53]. These effects are corrected for as described in End Matter.

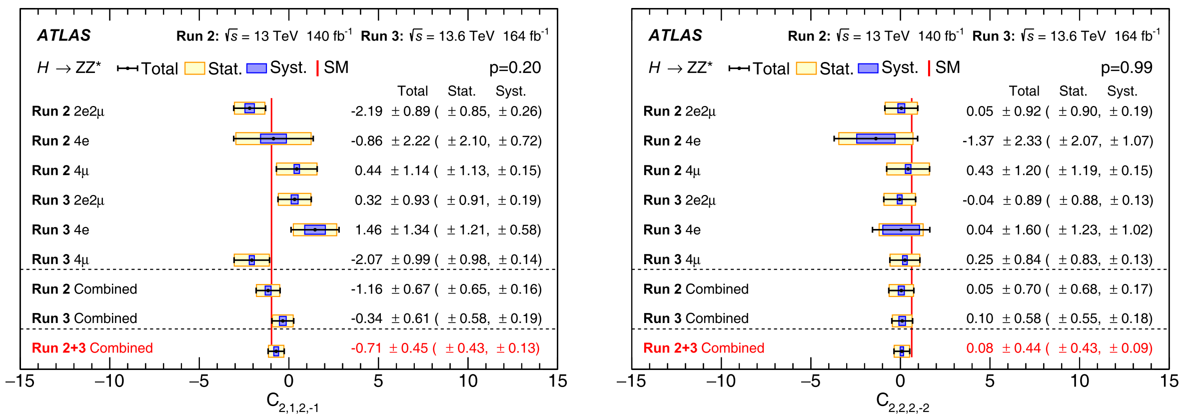
At leading order in perturbation theory and under the assumption described above, the density matrix of the ZZ^* system has a well-defined structure with only nine of the 81 elements being nonzero [11]. Of the six off-diagonal elements, the four that are products of $|0,0\rangle$ and $|\pm,\mp\rangle$ are equal to $\frac{1}{3}C_{2,1,2,-1}$, while the two that are products of $|+,-\rangle$ and $|-,+\rangle$ are equal to $\frac{1}{3}C_{2,2,2,-2}$. The Peres-Horodecki conditions [35,36] for the ZZ^* system then imply that the system is entangled if and only if at least one of the coefficients $C_{2,1,2,-1}$ or $C_{2,2,2,-2}$ is nonzero [11]. A nonzero value of either of them serves as a marker of entanglement in the ZZ^* system. The null hypothesis in which both coefficients vanish corresponds physically to the situation in which the Z bosons are in a pure separable $|00\rangle$ state, with a single remaining nonzero SDM element.

The sensitivity to entanglement from measurements of the coefficients $C_{2,1,2,-1}$ and $C_{2,2,2,-2}$ is limited, since they rely on estimating the mean of a broad underlying distribution using the mean of the data sample. To address this, an alternative approach is employed: the hypothesis of quantum entanglement (QE) as predicted by the Standard Model is tested against the null hypothesis of a separable system. This null hypothesis corresponds to the $|00\rangle$ state, the only separable ("non-QE") quantum state consistent



(a) $c_{2,1,2,-1}$ (b) $c_{2,2,2,-2}$

FIG. 4. The observed distributions of events (full circles) overlaid on the expected (shaded) distributions of the estimator (a) $c_{2,1,2,-1}$ and (b) $c_{2,2,2,-2}$ for the entangled hypothesis (blue solid line) and the separable non-QE hypothesis (orange dashed line) and background.



(a) $C_{2,1,2,-1}$ (b) $C_{2,2,2,-2}$

FIG. 5. Observed values of (a) $C_{2,1,2,-1}$ and (b) $C_{2,2,2,-2}$ in the Run 2 and Run 3 datasets and their combination, together with the corresponding individual measurements. The p values are calculated using the χ^2 statistic for the six channels.

with the stated assumptions–transitions to the other possible separable states $|+-\rangle$ or $|-+\rangle$ would violate CP. The full distribution of the $c_{2,2,2,-2}$ observable is used, which provides about 20% higher expected sensitivity than using $c_{2,1,2,-1}$.

Based on the expected distributions of the $c_{2,2,2,-2}$ observable for each of the two hypotheses, large ensembles of pseudoexperiment datasets are produced, with event yields in each analysis bin sampled according to Poisson statistics around the expected values. All theoretical and experimental systematic uncertainties enter as nuisance parameters (NPs) with Gaussian constraints. The test statistic for the hypothesis test $\tilde{q} = -2\ln(\mathcal{L}_{|00\rangle}/\mathcal{L}_{\mathrm{QE}})$ is then computed for each pseudoexperiment by profiling the ratio of the two likelihoods $\mathcal{L}_{|00\rangle}$ and $\mathcal{L}_{\mathrm{QE}}$ over the NPs, with the overall normalization of the $H \to ZZ^* \to 4\ell$ process being treated as a free parameter. The likelihood fit is performed simultaneously in two separate signal regions defined by requirements on the dilepton mass: $m_{Z_2} < 30$ GeV and $m_{Z_2} > 30$ GeV. This additional event classification makes better statistical use of the predicted larger contribution of transverse polarisation components in the SM at higher m_{Z_2}. Within the stated assumptions regarding the scalar nature of the Higgs boson and the SM chiral couplings in the Z boson decays, the m_{Z_2} spectrum for the purely longitudinal $|00\rangle$ configuration, the only separable state allowed, is expected to be shifted toward lower values compared to the SM entanglement configuration [37], so the m_{Z_2} distribution also indirectly probes the entanglement of the ZZ^* system. The split of the signal region leads to an improvement in sensitivity of about 15% in the rejection of the purely longitudinal configuration. The improvement arises primarily from differences in the expected angular distributions across the different m_{Z_2} selections, while the m_{Z_2} distribution itself contributes noticeably less. The resulting $\tilde{q}$ distributions for

TABLE I. Observed and expected values of the entanglement-sensitive spin-density-matrix coefficients are shown, together with their dominant systematic and statistical uncertainties. The "combined" columns show the results for $2e2\mu + 4e + 4\mu$. The results are for the combined datasets from Run 2 and Run 3. The observed and predicted values for the $4e + 4\mu$ channels are shown after the corrections $\Delta C^{\mathrm{interf}}$ for interference effects have been applied as described in End Matter. The SM expected values are calculated from the Monte Carlo simulation.

Coefficient	$C_{2,1,2,-1}$			$C_{2,2,2,-2}$		
Channel	$2e2\mu$	$4e+4\mu$	Combined	$2e2\mu$	$4e+4\mu$	Combined
Observed	-0.98 ± 0.64	-0.44 ± 0.63	-0.71 ± 0.45	0.00 ± 0.64	0.15 ± 0.61	0.08 ± 0.44
SM expected		-0.97			0.64	
Leading uncertainty components						
Fake-lepton background	± 0.16	± 0.16	± 0.12	± 0.11	± 0.18	± 0.12
Irreducible background	± 0.05	± 0.04	± 0.04	± 0.01	± 0.01	± 0.01
Interference	Not applicable	± 0.04	± 0.02	Not applicable	± 0.03	± 0.02
EW NLO effects	± 0.02	± 0.01	± 0.01	< 0.01	< 0.01	< 0.01
Migration	± 0.01	± 0.02	± 0.01	± 0.01	± 0.02	± 0.01
Statistical	± 0.62	± 0.61	± 0.43	± 0.63	± 0.58	± 0.43

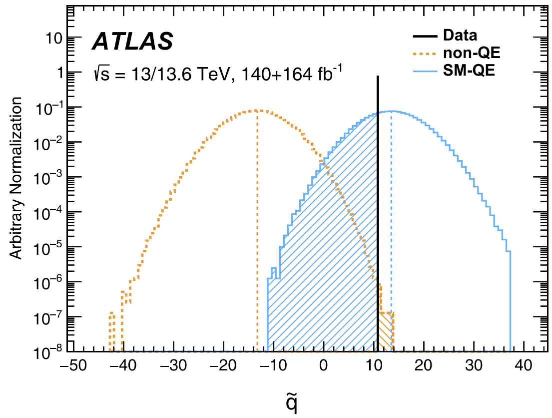


FIG. 6. Distribution of the test statistic $\tilde{q}$ for the entangled (blue solid line) and nonentangled (orange dashed line) hypotheses, as obtained from 10 million pseudoexperiments. The observed value is indicated by a vertical full line, and the expected values for each of the two hypotheses are indicated with vertical dashed lines.

the simulations of the QE and the $|00\rangle$ hypotheses are compared to determine the confidence level for rejecting the nonentangled hypothesis using the C.L.$_s$ method [54].

The event-by-event distributions of the entanglement-sensitive observables $c_{2,2,2,-2}$ and $c_{2,1,2,-1}$ are shown in Fig. 4, inclusively for the combination of both Z_2 signal regions. The agreement between data and prediction for the relevant mass and angular distributions has been validated in previous measurements [55,56]. The resulting parton-level SDM coefficients, together with their statistical and systematic uncertainties, are evaluated separately for the three decay channels ($4e$, 4μ, $2e2\mu$) and for the two data sets (Run 2, Run 3) and are then combined for the entanglement interpretation. A summary of all six individual measurements and their combinations is shown in Fig. 5, separately for the $C_{2,1,2,-1}$ and $C_{2,2,2,-2}$ coefficients. The combinations are implemented using the best linear unbiased estimate technique [57]. The observed combined values of the coefficients, shown in Table I together with their uncertainties, are found to be consistent between channels and consistent with the Standard Model predictions. The systematic uncertainties are all substantially smaller than the statistical uncertainties.

The likelihood-ratio test has substantially higher sensitivity to the entangled SM hypothesis relative to the separable $|00\rangle$ hypothesis because it makes use of the full shape of the $c_{2,2,2,-2}$ distribution, rather than just its mean value. The expected distributions of the test statistic $\tilde{q}$ for the two hypotheses are shown in Fig. 6, together with the observed value. With all uncertainties taken into account, and based on 10 million pseudoexperiments per hypothesis, the hypothesis of a nonentangled quantum state with purely longitudinally polarized Z bosons is rejected with a significance of 4.7σ (expected 4.9σ) in favor of the quantum-entanglement hypothesis predicted by the Standard Model.

In conclusion, these results constitute the first measurements of quantum entanglement between two massive vector bosons at the electroweak scale. The distinctive chiral structure of the SM weak force provides access to the ZZ^* SDM in $H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$ decays. The results show how quantum coherence, previously observed in fermionic systems such as top-quark pairs, extends to heavy spin-1 bosons in fundamental particle interactions. With the larger datasets expected from the full Run 3 and the high-luminosity LHC, future analyses will enable more precise tests and sensitivity to potential deviations from the Standard Model.

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End Matter

Appendix A: Simulation and background prediction—Monte Carlo (MC) simulated signal samples for the Standard Model Higgs boson are simulated using POWHEG BOX v2 [59] interfaced to PYTHIA 8 [60] with the dedicated Hto4l [61] decay library providing full spin correlations in $H \to ZZ^* \to 4\ell$ decays. The dominant gluon-gluon fusion (ggF) process is simulated at next-to-next-to-leading order (NNLO) in quantum chromodynamics (QCD) [62,63], while vector-boson fusion (VBF) [64] and associated production (VH) are simulated at next-to-leading order (NLO). Minor production modes of Higgs bosons in association with top and bottom quarks, including $t\bar{t}H$, tH, and $b\bar{b}H$, are simulated at NLO using POWHEG BOX v2 + PYTHIA 8. Final-state radiation is simulated within Hto4l and PYTHIA 8. Its impact on the reconstructed angular observables was found to be below 1%.

The samples are normalized to state-of-the-art cross-section predictions for the center-of-mass energy of 13 TeV [65] and these predictions are extrapolated to 13.6 TeV. The ggF sample is normalized to a N^{3}LO QCD calculation with NLO electroweak (EW) corrections [66–77]. The VBF sample is normalized to an approximate NNLO QCD cross section with NLO EW corrections [78–80]. The VH samples are normalized to cross-sections calculated at NNLO in QCD with NLO EW corrections [81–88]. The $b\bar{b}H$ contribution is normalized to a calculation that combines the complete NLO contributions that are present in the four-flavor scheme calculation, including finite b-quark mass effects and top-loop induced top-to-bottom Yukawa-coupling interference contributions, with the resummation of collinear logarithms of m_b/m_H as present in the five-flavor scheme calculation up to NNLO [89–93]. No EW corrections are included for $b\bar{b}H$, tH, or tWH.

Irreducible backgrounds from nonresonant $Z^{(*)}Z^{(*)}$ production are modeled using Sherpa 2.2.16 [94–96], with a matrix element calculated at NLO in the strong coupling α_s for final states with up to one additional parton, and at LO accuracy for up to three additional partons. The matrix element (ME) calculations used OpenLoops [96] for the virtual QCD corrections, and were merged with the Sherpa parton shower using the ME+PS@NLO prescription [97]. The loop-induced gluon-initiated ZZ process ($gg \to ZZ$) was simulated with POWHEG BOX v2 + PYTHIA 8 at NLO precision.

Production of $t\bar{t}Z$ and tri-boson (VVV) production, where V represents $W^{\pm}$ or Z, are both modeled with Sherpa 2.2.12, requiring at least four charged leptons in the final state. Backgrounds with nonprompt leptons arise primarily from Z boson production with associated jets ($Z+$jets), production of WZ and $t\bar{t}$. The production of $Z+$jets was simulated using Sherpa 2.2.14 with up to two partons at NLO and five partons at LO in α_s. The WZ process was simulated using Sherpa 2.2.16, with a similar configuration as used for the $q\bar{q} \to Z^{(*)}Z^{(*)}$ process. Events of $t\bar{t}$ production were simulated with POWHEG BOX v2 + PYTHIA 8.3 at NLO in α_s.

For the test of the quantum-entanglement hypothesis, additional dedicated samples are produced using MadGraph5_aMC@NLO [98] enforcing longitudinal polarization of both $Z^{(*)}$ bosons. They are parton-showered with PYTHIA 8 and reweighted to match the production kinematic spectra of the POWHEG-based inclusive SM Higgs-boson samples.

The reducible background arises when events with fewer than four prompt leptons satisfy the signal region event selection criteria because jets or photons are misidentified as leptons or due to non-prompt leptons from heavy-flavor hadron decays. Since such backgrounds may not be well modeled in simulation, this contribution is estimated with a data-driven fake-factor (FF) method [99] rather than from direct MC simulation. The FF is measured in two dedicated control regions enriched, respectively, in $Z+$jets (CR Z) and in top-pair production (CR top). Systematic uncertainties include the variation of the control region for the FF measurement (CR Z or CR top), the statistical uncertainty in the measurement CRs, and the statistical uncertainty in the application regions. The total uncertainty in the reducible background estimate in the signal region is 39% for the Run 2 data and 46% for the Run 3 data.

Appendix B: Calibration corrections and systematic uncertainties—The procedure for evaluating the SDM elements is as follows. First, the mean value $C_{\mathrm{ch}}^{\mathrm{data,reco}}$ of the entanglement-sensitive angular distribution $c_{\mathrm{ch}}^{\mathrm{data,reco}}$ is calculated using all events that satisfy the event selection criteria. The index "ch" denotes the individual decay channel, $4e$, 4μ, or $2e2\mu$. Next, the reconstructed mean value $C_{\mathrm{ch}}^{\mathrm{data,reco}}$ is corrected for background effects, using their predicted yields and mean values of the coefficient, resulting in a reconstructed value $C_{\mathrm{ch}}^{\mathrm{H}4\ell,\mathrm{reco}}$ for the Higgs-boson signal alone. The statistical and systematic uncertainty in all background contributions are propagated. The reconstructed coefficient $C_{\mathrm{ch}}^{\mathrm{H}4\ell,\mathrm{reco}}$ is calibrated to the "parton" (i.e., leptons before quantum electrodynamics radiation) level value using a set of linear calibrations, one for each channel for each LHC run period (i.e., Run 2 and Run 3), obtained from $c_{\mathrm{ch}}^{\mathrm{H}4\ell,\mathrm{MC}}$ weighted simulations of Standard Model Higgs-boson signal samples. The systematic uncertainty of the calibration procedure is evaluated and taken into account. For same-flavor decay channels, the correction $\Delta C^{\mathrm{interf}} = C_{2e2\mu}^{\mathrm{MC}} - C_{4e/4\mu}^{\mathrm{MC}}$ is applied to account for interference effects, where the corrections are found from simulation to be $\Delta C_{2,1,2,-1}^{\mathrm{interf}} = -0.07$ and $\Delta C_{2,2,2,-2}^{\mathrm{interf}} = 0.06$. A conservative symmetrical systematic uncertainty equal to 50% of this correction is assigned to the same-flavor channels ($4e$ and 4μ). Finally, an additional multiplicative systematic uncertainty is introduced to account for effects from electroweak corrections at NLO. This uncertainty is taken as the difference between LO and NLO EW predictions [42], corresponding to multiplicative uncertainties of 1.1% for $C_{2,1,2,-1}$ and 1.4% for $C_{2,2,2,-2}$.

Experimental systematic uncertainties are accounted for including lepton calibration and acceptance, luminosity, as well as the effect of pileup [45]. Uncertainties in the yield of fake- and nonprompt leptons are estimated using dedicated control regions. For the combined measurement of each SDM coefficient, the statistical uncertainties, including those on the fake-lepton estimate, and the systematic uncertainty from unfolding are each treated as uncorrelated between flavor channels and between LHC run periods. The uncertainties from biases from the interference (where present) and those from NLO EW correction are treated as fully correlated between flavor channels and run periods. The systematic uncertainties resulting from the background subtraction and from the fake-lepton estimate closure are treated as fully correlated between flavor channels and uncorrelated between run periods.

For the hypothesis test, the overall impact from all sources of systematic uncertainties is indicated by the uncertainty band in Fig. 4. The dominant theoretical uncertainty originates from the theoretical contribution from higher-order terms in QCD, and corresponds to approximately 10% of the predicted yield. Subleading systematic uncertainties include those from the MC parton shower modeling and reducible background (fake-lepton) related uncertainties. Experimental uncertainties are found to be subdominant and are found not to materially change the shape of the distributions. They are therefore represented by a conservative overall 3% uncertainty.

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S. Strandberg,[46a,46b] M. Stratmann,[173] M. Strauss,[121] T. Strebler,[102] P. Strizenec,[29b] R. Ströhmer,[168] D. M. Strom,[124] R. Stroynowski,[44] A. Strubig,[46a,46b] S. A. Stucci,[30] B. Stugu,[17] J. Stupak,[121] N. A. Styles,[47] D. Su,[146] S. Su,[61] X. Su,[61] D. Suchy,[29a] A. D. Sudhakar Ponnu,[54] L. Sudit,[171] Y. Sue,[82] K. Sugizaki,[129] D. M. S. Sultan,[127] L. Sultanaliyeva,[25] S. Sultansoy,[3b] S. Sun,[172] W. Sun,[14] S. Sundar Raman,[166] N. Sur,[98] J. P. Surdutovich,[120] N. Suri Jr.,[174] M. R. Sutton,[149] M. Svatos,[132] P. N. Swallow,[33] S. N. Swatman,[37] M. Swiatlowski,[159a] A. Swoboda,[37] I. Sykora,[29a] M. Sykora,[134] T. Sykora,[134] D. Ta,[100] K. Tackmann,[47,qq] A. Taffard,[162] R. Tafirout,[159a] Y. Takubo,[82] M. Talby,[102] N. M. Tamir,[154] A. Tanaka,[156] J. Tanaka,[156] R. Tanaka,[65] M. Tanasini,[148] Z. Tao,[166] S. Tapia Araya,[138g] S. Tapprogge,[100] A. Tarek Abouelfadl Mohamed,[37] S. Tarem,[153] K. Tariq,[14] G. Tarna,[37] G. F. Tartarelli,[70a] M. J. Tartarin,[141b] P. Tas,[134] M. Tasevsky,[132] E. Tassi,[43b,43a] A. C. Tate,[164] Y. Tayalati,[36e,rr] G. N. Taylor,[105] W. Taylor,[159b] R. J. Taylor Vara,[165] A. S. Tegetmeier,[89] P. Teixeira-Dias,[95] J. J. Teoh,[158] K. Terashi,[156] J. Terron,[99] S. Terzo,[13] M. Testa,[52] R. J. Teuscher,[158,p] A. Thaler,[78] T. Theveneaux-Pelzer,[102] J. P. Thomas,[21] E. A. Thompson,[18a] P. D. Thompson,[21] E. Thomson,[129] R. E. Thornberry,[30] T. M. Thory-Rao,[21] C. N. Thotamuna Wijewardhana,[148] C. Tian,[61] Y. Tian,[55] V. Tikhomirov,[80] Yu. A. Tikhonov,[38] D. Timoshyn,[134] E. X. L. Ting,[1] P. Tipton,[174] A. Tishelman-Charny,[30] K. Todome,[139] S. Todorova-Nova,[134] L. Toffolin,[68a,68c] M. Togawa,[82] J. Tojo,[88] S. Tokár,[29a] O. Toldaiev,[67] G. Tolkachev,[102] M. Tomoto,[82] L. Tompkins,[146] E. Torrence,[124] H. Torres,[89] D. I. Torres Arza,[138g] E. Torres Reoyo,[165] E. Torró Pastor,[165] M. Toscani,[31] C. Tosciri,[39] M. Tost,[11] D. R. Tovey,[142] T. Trefzger,[168] P. M. Tricarico,[13] A. Tricoli,[30] I. M. Trigger,[159a] S. Trincaz-Duvoid,[128] D. A. Trischuk,[167] A. Tropina,[38] D. Truncali,[75a,75b] L. Truong,[34c] M. Trzebinski,[86] A. Trzupek,[86] F. Tsai,[148] A. Tsiamis,[155] P. V. Tsiareshka,[38] S. Tsigaridas,[159a] A. Tsirigotis,[155,ff] V. Tsiskaridze,[152a] E. G. Tskhadadze,[152a] H. F. Tsoi,[129] Y. Tsujikawa,[87] V. Tsulaia,[18a] K. Tsuri,[119] D. Tsybychev,[148] Y. Tu,[63b] A. Tudorache,[28b] V. Tudorache,[28b] S. B. Tuncay,[127] S. Turchikhin,[56b,56a] I. Turk Cakir,[3a] R. Turra,[70a] T. Turtuvshin,[38,ss] P. M. Tuts,[41] Y. Uematsu,[82] F. Ukegawa,[160] P. A. Ulloa Poblete,[138c,138b] G. Unal,[37] A. Undrus,[30] J. Urban,[29b] P. Urrejola,[138e] G. Usai,[8] R. Ushioda,[157] M. Usman,[108] F. Ustuner,[51] Z. Uysal,[80] V. Vacek,[133] B. Vachon,[104] T. Vafeiadis,[37] A. Vaitkus,[96] C. Valderanis,[109] E. Valdes Santurio,[46a,46b] M. Valente,[37] S. Valentinetti,[24b,24a] A. Valero,[165] E. Valiente Moreno,[165] A. Vallier,[89] J. A. Valls Ferrer,[165] D. R. Van Arneman,[116] R. Van Den Broucke,[128] A. Van Der Graaf,[48] H. Z. Van Der Schyf,[34j] P. Van Gemmeren,[6] M. Van Rijnbach,[37] S. Van Stroud,[96] I. Van Vulpen,[116] P. Vana,[134] M. Vanadia,[75a,75b] U. M. Vande Voorde,[147] W. Vandelli,[37] E. R. Vandewall,[146] D. Vannicola,[154] R. Vari,[74a] M. Varma,[174] E. W. Varnes,[7] C. Varni,[85a] D. Varouchas,[65] L. Varriale,[165] K. E. Varvell,[150] M. E. Vasile,[28b] A. Vasileiadou,[9] L. Vaslin,[82] M. D. Vassilev,[146] A. Vasyukov,[38] L. M. Vaughan,[122] R. Vavricka,[134] T. Vazquez Schroeder,[13] J. Veatch,[32] V. Vecchio,[101] M. J. Veen,[103] I. Veliscek,[30] I. Velkovska,[93] L. M. Veloce,[158] F. Veloso,[131a,131c] A. G. Veltman,[51] S. H. Venetianer,[161] S. Veneziano,[74a] A. Ventura,[69a,69b] A. Verbytskyi,[110] M. Verducci,[73a,73b] C. Vergis,[94] M. Verissimo De Araujo,[81b] W. Verkerke,[116] J. C. Vermeulen,[116] C. Vernieri,[146] M. Vessella,[162] M. C. Vetterli,[145,u] A. Vgenopoulos,[100] N. Viaux Maira,[138g,tt] L. Vicenik,[133] T. Vickey,[142] O. E. Vickey Boeriu,[142] G. H. A. Viehhauser,[127] L. Vigani,[62b] M. Vigl,[110] M. Villa,[24b,24a] M. Villaplana Perez,[165] E. M. Villhauer,[39] E. Vilucchi,[52] M. Vincent,[165] M. G. Vincter,[35] A. Visibile,[116] A. Visive,[116] C. Vittori,[161] I. Vivarelli,[24b,24a] M. I. Vivas Albornoz,[47] E. Voevodina,[110] F. Vogel,[109] J. C. Voigt,[49] P. Vokac,[133] Yu. Volkotrub,[85b] L. Vomberg,[25] E. Von Toerne,[25] B. Vormwald,[37] K. Vorobev,[50] M. Vos,[165] K. Voss,[144] M. Vozak,[37] L. Vozdecky,[121] N. Vranjes,[16] M. Vranjes Milosavljevic,[16] M. Vreeswijk,[116] N. K. Vu,[112a] R. Vuillermet,[37] O. Vujinovic,[100] I. Vukotic,[39] I. K. Vyas,[35] J. F. Wack,[33] A. Wada,[111] S. Wada,[160] C. Wagner,[146] J. M. Wagner,[18a] W. Wagner,[173] S. Wahdan,[173] H. Wahlberg,[90] C. H. Waits,[121] J. Walder,[135] R. Walker,[109] K. Walkingshaw Pass,[58] W. Walkowiak,[144] A. Wall,[129] E. J. Wallin,[98] T. Wamorkar,[146] K. Wandall-Christensen,[165] A. Wang,[61] A. Z. Wang,[137] C. Wang,[47] C. Wang,[11] H. Wang,[18a] J. Wang,[63c] P. Wang,[101] P. Wang,[96] R. Wang,[60] R. Wang,[106] R. Wang,[6] S. M. Wang,[151] S. Wang,[14] T. Wang,[115] T. Wang,[61] W. T. Wang,[127] W. Wang,[113c] X. Wang,[164] X. Wang,[141a] X. Wang,[47] Y. Wang,[148] Y. Wang,[114] Z. Wang,[106] Z. Wang,[14] Z. Wang,[63b] C. Wanotayaroj,[82] A. Warburton,[104] A. L. Warnerbring,[144] S. Waterhouse,[96] A. T. Watson,[21] H. Watson,[51] M. F. Watson,[21] E. Watton,[37] G. Watts,[140] B. M. Waugh,[96] J. M. Webb,[53] C. Weber,[30] M. S. Weber,[20] C. Wei,[61] Y. Wei,[53] A. R. Weidberg,[127] E. J. Weik,[118] J. Weingarten,[48] C. Weiser,[53] C. J. Wells,[47] P. S. Wells,[37] T. Wenaus,[30] T. Wengler,[37] N. S. Wenke,[110]

N. Wermes,[25] D. Werner,[47] M. Wessels,[62a] A. M. Wharton,[91] A. S. White,[37] A. White,[8] M. J. White,[1] D. Whiteson,[162] L. Wickremasinghe,[125] W. Wiedenmann,[172] M. Wielers,[135] R. Wierda,[147] C. Wiglesworth,[42] H. G. Wilkens,[37] J. J. H. Wilkinson,[33] S. Williams,[33] S. Willocq,[103] D. J. Wilson,[101] P. J. Windischhofer,[39] F. I. Winkel,[31] F. Winklmeier,[124] B. T. Winter,[53] M. Wittgen,[146] M. Wobisch,[97] T. Wojtkowski,[59] Z. Wolffs,[116] J. Wollrath,[37] M. W. Wolter,[86] H. Wolters,[131a,131c] M. C. Wong,[137] E. L. Woodward,[41] S. D. Worm,[47] B. K. Wosiek,[86] K. A. Wozniak,[55] K. W. Woźniak,[86] S. Wozniewski,[54] K. Wraight,[58] C. Wu,[158] C. Wu,[21] J. Wu,[156] M. Wu,[112b] M. Wu,[115] S. L. Wu,[172] S. Wu,[14,uu] X. Wu,[61] Y. Q. Wu,[158] Y. Wu,[61] Z. Wu,[102] Z. Wu,[112a] J. Wuerzinger,[110] T. R. Wyatt,[101] B. M. Wynne,[51] S. Xella,[42] L. Xia,[112a] M. Xie,[61] A. Xiong,[124] I. Xiotidis,[37] D. Xu,[14] H. Xu,[61] L. Xu,[61] R. Xu,[129] T. Xu,[106] W. Xu,[112a] Y. Xu,[140] Z. Xu,[51] R. Xue,[130] B. Yabsley,[150] S. Yacoob,[11] Y. Yamaguchi,[82] E. Yamashita,[156] H. Yamauchi,[160] T. Yamazaki,[18a] Y. Yamazaki,[84] S. Yan,[58] Z. Yan,[103] C. Yang,[18a] H. J. Yang,[141a] H. T. Yang,[61] S. Yang,[61] X. Yang,[37] X. Yang,[14] Y. Yang,[156] Y. Yang,[61] W-M. Yao,[18a] C. L. Yardley,[149] J. Ye,[14] S. Ye,[30] X. Ye,[61] I. Yeletskikh,[38] B. Yeo,[18b] M. R. Yexley,[96] T. P. Yildirim,[127] K. Yorita,[170] C. J. S. Young,[37] C. Young,[146] I. N. L. Young,[58] N. D. Young,[124] Y. Yu,[61] J. Yuan,[14,112c,uu] M. Yuan,[106] R. Yuan,[141b] L. Yue,[96] M. Zaazoua,[61] B. Zabinski,[86] I. Zahir,[36a] Q. U. A. Zahoor,[51] A. Zaio,[56b,56a] Z. K. Zak,[86] T. Zakareishvili,[165] S. Zambito,[55] J. Zang,[156] R. Zanzottera,[70a,70b] O. Zaplatilek,[133] E. Zaya,[147] C. Zeitnitz,[173] H. Zeng,[14] D. T. Zenger Jr.,[27] T. Ženiš,[29a] S. Zenz,[94] D. Zerwas,[65] W. Zhan,[61] B. Zhang,[169] D. F. Zhang,[142] G. Zhang,[14,uu] J. Zhang,[113b] J. Zhang,[6] L. Zhang,[61] L. Zhang,[112a] P. Zhang,[14,112c] R. Zhang,[112a] S. Zhang,[36e] Y. Zhang,[140] Y. Zhang,[96] Y. Zhang,[61] Y. Zhang,[112a] Z. Zhang,[18a] Z. Zhang,[113b] Z. Zhang,[65] H. Zhao,[140] T. Zhao,[113b] Y. Zhao,[35] Z. Zhao,[61] Z. Zhao,[61] A. Zhemchugov,[38] J. Zheng,[112a] K. Zheng,[164] L. Zheng,[113b] X. Zheng,[61] Z. Zheng,[146] D. Zhong,[164] B. Zhou,[106] B. Zhou,[141b,141a] N. Zhou,[141a] Y. Zhou,[15] Y. Zhou,[112a] Y. Zhou,[7] Z. Zhou,[61] J. Zhu,[106] X. Zhu,[141b] Y. Zhu,[141a] X. Zhuang,[14] K. Zhukov,[67] P. Ziakas,[4] N. I. Zimine,[38] J. Zinsser,[62b] M. Ziolkowski,[144] L. Živković,[16] A. Zoccoli,[24b,24a] K. Zoch,[37] A. Zografos,[37] T. G. Zorbas,[142] and L. Zwalinski[37]

(ATLAS Collaboration)

[1]*Department of Physics, University of Adelaide, Adelaide, Australia*
[2]*Department of Physics, University of Alberta, Edmonton, Alberta, Canada*
[3a]*Department of Physics, Ankara University, Ankara, Türkiye*
[3b]*Division of Physics, TOBB University of Economics and Technology, Ankara, Türkiye*
[4]*LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France*
[5]*APC, Université Paris Cité, CNRS/IN2P3, Paris, France*
[6]*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA*
[7]*Department of Physics, University of Arizona, Tucson, Arizona, USA*
[8]*Department of Physics, University of Texas at Arlington, Arlington, Texas, USA*
[9]*Physics Department, National and Kapodistrian University of Athens, Athens, Greece*
[10]*Physics Department, National Technical University of Athens, Zografou, Greece*
[11]*Department of Physics, University of Texas at Austin, Austin, Texas, USA*
[12]*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
[13]*Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain*
[14]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*
[15]*Physics Department, Tsinghua University, Beijing, China*
[16]*Institute of Physics, University of Belgrade, Belgrade, Serbia*
[17]*Department for Physics and Technology, University of Bergen, Bergen, Norway*
[18a]*Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA*
[18b]*University of California, Berkeley, California, USA*
[19]*Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany*
[20]*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
[21]*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[22a]*Department of Physics, Bogazici University, Istanbul, Türkiye*
[22b]*Department of Physics Engineering, Gaziantep University, Gaziantep, Türkiye*
[22c]*Department of Physics, Istanbul University, Istanbul, Türkiye*
[23a]*Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá, Colombia*

[23b]*Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia*
[24a]*Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna, Italy*
[24b]*INFN Sezione di Bologna, Bologna, Italy*
[25]*Physikalisches Institut, Universität Bonn, Bonn, Germany*
[26]*Department of Physics, Boston University, Boston, Massachusetts, USA*
[27]*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
[28a]*Transilvania University of Brasov, Brasov, Romania*
[28b]*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[28c]*Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania*
[28d]*National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania*
[28e]*National University of Science and Technology Politechnica, Bucharest, Romania*
[28f]*West University in Timisoara, Timisoara, Romania*
[28g]*Faculty of Physics, University of Bucharest, Bucharest, Romania*
[29a]*Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic*
[29b]*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
[30]*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
[31]*Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina*
[32]*California State University, Fresno, California, USA*
[33]*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[34a]*Department of Physics, University of Cape Town, Cape Town, South Africa*
[34b]*iThemba Labs, Western Cape, South Africa*
[34c]*Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa*
[34d]*National Institute of Physics, University of the Philippines Diliman (Philippines), Quezon City, Philippines*
[34e]*Department of Physics, Stellenbosch University, Matieland, South Africa*
[34f]*University of KwaZulu-Natal, School of Agriculture and Science, Mathematics, Westville, South Africa*
[34g]*University of South Africa, Department of Physics, Pretoria, South Africa*
[34h]*University of Pretoria, Department of Mechanical and Aeronautical Engineering, Pretoria, South Africa*
[34i]*University of Zululand, KwaDlangezwa, South Africa*
[34j]*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
[35]*Department of Physics, Carleton University, Ottawa, Ontario, Canada*
[36a]*Faculté des Sciences Ain Chock, Université Hassan II de Casablanca, Casablanca, Morocco*
[36b]*Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco*
[36c]*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
[36d]*LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda, Morocco*
[36e]*Faculté des sciences, Université Mohammed V, Rabat, Morocco*
[36f]*Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco*
[37]*CERN, Geneva, Switzerland*
[38]*Affiliated with an international laboratory covered by a cooperation agreement with CERN*
[39]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA*
[40]*LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France*
[41]*Nevis Laboratory, Columbia University, Irvington New York, USA*
[42]*Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
[43a]*Dipartimento di Fisica, Università della Calabria, Rende, Italy*
[43b]*INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Frascati, Italy*
[44]*Physics Department, Southern Methodist University, Dallas, Texas, USA*
[45]*National Centre for Scientific Research "Demokritos", Agia Paraskevi, Greece*
[46a]*Department of Physics, Stockholm University, Sweden*
[46b]*Oskar Klein Centre, Stockholm, Sweden*
[47]*Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany*
[48]*Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
[49]*Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
[50]*Department of Physics, Duke University, Durham, North Carolina, USA*
[51]*SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
[52]*INFN e Laboratori Nazionali di Frascati, Frascati, Italy*
[53]*Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
[54]*II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
[55]*Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland*
[56a]*Dipartimento di Fisica, Università di Genova, Genova, Italy*

[56b]*INFN Sezione di Genova, Genova, Italy*
[57]*II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
[58]*SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
[59]*LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France*
[60]*Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA*
[61]*Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China*
[62a]*Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[62b]*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[63a]*Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China*
[63b]*Department of Physics, University of Hong Kong, Hong Kong, China*
[63c]*Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
[64]*Department of Physics, National Tsing Hua University, Hsinchu, Taiwan*
[65]*IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France*
[66]*Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona, Spain*
[67]*Department of Physics, Indiana University, Bloomington, Indiana, USA*
[68a]*INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy*
[68b]*ICTP, Trieste, Italy*
[68c]*Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy*
[69a]*INFN Sezione di Lecce, Lecce, Italy*
[69b]*Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
[70a]*INFN Sezione di Milano, Milano, Italy*
[70b]*Dipartimento di Fisica, Università di Milano, Milano, Italy*
[71a]*INFN Sezione di Napoli, Napoli, Italy*
[71b]*Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
[72a]*INFN Sezione di Pavia, Pavia, Italy*
[72b]*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
[73a]*INFN Sezione di Pisa, Pisa, Italy*
[73b]*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
[74a]*INFN Sezione di Roma, Roma, Italy*
[74b]*Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
[75a]*INFN Sezione di Roma Tor Vergata, Roma, Italy*
[75b]*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
[76a]*INFN Sezione di Roma Tre, Roma, Italy*
[76b]*Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
[77a]*INFN-TIFPA, Trento, Italy*
[77b]*Università degli Studi di Trento, Trento, Italy*
[78]*Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck, Austria*
[79]*Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA*
[80]*Istinye University, Sariyer, Istanbul, Türkiye*
[81a]*Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil*
[81b]*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
[81c]*Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*
[81d]*Rio de Janeiro State University, Rio de Janeiro, Brazil*
[81e]*Federal University of Bahia, Bahia, Brazil*
[82]*KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
[83a]*Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates*
[83b]*New York University Abu Dhabi, Abu Dhabi, United Arab Emirates*
[83c]*United Arab Emirates University, Al Ain, United Arab Emirates*
[83d]*University of Sharjah, Sharjah, United Arab Emirates*
[84]*Graduate School of Science, Kobe University, Kobe, Japan*
[85a]*AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow, Poland*
[85b]*Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
[86]*Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
[87]*Faculty of Science, Kyoto University, Kyoto, Japan*
[88]*Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
[89]*L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse, France*
[90]*Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
[91]*Physics Department, Lancaster University, Lancaster, United Kingdom*

[92]Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[93]Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
[94]Department of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
[95]Department of Physics, Royal Holloway University of London, Egham, United Kingdom
[96]Department of Physics and Astronomy, University College London, London, United Kingdom
[97]Louisiana Tech University, Ruston, Louisiana, USA
[98]Fysiska institutionen, Lunds universitet, Lund, Sweden
[99]Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
[100]Institut für Physik, Universität Mainz, Mainz, Germany
[101]School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[102]CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
[103]Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
[104]Department of Physics, McGill University, Montreal, Quebec, Canada
[105]School of Physics, University of Melbourne, Victoria, Australia
[106]Department of Physics, University of Michigan, Ann Arbor, Michigan, USA
[107]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
[108]Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada
[109]Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[110]Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
[111]Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
[112a]Department of Physics, Nanjing University, Nanjing, China
[112b]School of Science, Shenzhen Campus of Sun Yat-sen University, China
[112c]University of Chinese Academy of Science (UCAS), Beijing, China
[113a]School of Physics, Nankai University, Tianjin, China
[113b]Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China
[113c]School of Physics, Zhengzhou University, Zhengzhou, China
[114]Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
[115]Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands
[116]Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
[117]Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
[118]Department of Physics, New York University, New York, New York, USA
[119]Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan
[120]Ohio State University, Columbus, Ohio, USA
[121]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
[122]Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
[123]Palacký University, Joint Laboratory of Optics, Olomouc, Czech Republic
[124]Institute for Fundamental Science, University of Oregon, Eugene, Oregon, USA
[125]Graduate School of Science, University of Osaka, Osaka, Japan
[126]Department of Physics, University of Oslo, Oslo, Norway
[127]Department of Physics, Oxford University, Oxford, United Kingdom
[128]LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris, France
[129]Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
[130]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
[131a]Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal
[131b]Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
[131c]Departamento de Física, Universidade de Coimbra, Coimbra, Portugal
[131d]Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
[131e]Departamento de Física, Escola de Ciências, Universidade do Minho, Braga, Portugal
[131f]Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain
[131g]Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
[132]Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[133]Czech Technical University in Prague, Prague, Czech Republic
[134]Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
[135]Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[136]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
[137]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
[138a]Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
[138b]Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago, Chile

[138c]*Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena, Chile*
[138d]*Universidad Andres Bello, Department of Physics, Santiago, Chile*
[138e]*Universidad San Sebastian, Recoleta, Chile*
[138f]*Instituto de Alta Investigación, Universidad de Tarapacá, Arica, Chile*
[138g]*Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
[139]*Department of Physics, Institute of Science, Tokyo, Japan*
[140]*Department of Physics, University of Washington, Seattle, Washington, USA*
[141a]*State Key Laboratory of Dark Matter Physics, School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai, China*
[141b]*State Key Laboratory of Dark Matter Physics, Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai, China*
[142]*Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
[143]*Department of Physics, Shinshu University, Nagano, Japan*
[144]*Department Physik, Universität Siegen, Siegen, Germany*
[145]*Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada*
[146]*SLAC National Accelerator Laboratory, Stanford, California, USA*
[147]*Department of Physics, Royal Institute of Technology, Stockholm, Sweden*
[148]*Departments of Physics and Astronomy, Stony Brook University, Stony Brook New York, USA*
[149]*Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
[150]*School of Physics, University of Sydney, Sydney, Australia*
[151]*Institute of Physics, Academia Sinica, Taipei, Taiwan*
[152a]*E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia*
[152b]*High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
[152c]*University of Georgia, Tbilisi, Georgia*
[153]*Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel*
[154]*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
[155]*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
[156]*International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan*
[157]*Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
[158]*Department of Physics, University of Toronto, Toronto, Ontario, Canada*
[159a]*TRIUMF, Vancouver, British Columbia, Canada*
[159b]*Department of Physics and Astronomy, York University, Toronto, Ontario, Canada*
[160]*Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*
[161]*Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*
[162]*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
[163]*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
[164]*Department of Physics, University of Illinois, Urbana, Illinois, USA*
[165]*Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain*
[166]*Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada*
[167]*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada*
[168]*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany*
[169]*Department of Physics, University of Warwick, Coventry, United Kingdom*
[170]*Waseda University, Tokyo, Japan*
[171]*Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel*
[172]*Department of Physics, University of Wisconsin, Madison WI, USA*
[173]*Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
[174]*Department of Physics, Yale University, New Haven, Connecticut, USA*
[175]*Yerevan Physics Institute, Yerevan, Armenia*

[a]Deceased.
[b]Also at Department of Physics, King's College London, London, United Kingdom.
[c]Associated at Instituto de Fisica Teorica, IFT-UAM/CSIC, Madrid, Spain.
[d]Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[e]Also at Imam Mohammad Ibn Saud Islamic University, Riyadh, Saudi Arabia.
[f]Also at Department of Physics, University of Thessaly, Volos, Greece.
[g]Also at An-Najah National University, Nablus, Palestine.
[h]Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
[i]Also at Department of Physics, Westmont College, Santa Barbara, California, USA.
[j]Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.
[k]Also at University of Siena, Siena, Italy.

[l]Also at Affiliated with an institute formerly covered by a cooperation agreement with CERN.
[m]Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
[n]Also at Faculty of Physics, Sofia University, "St. Kliment Ohridski", Sofia, Bulgaria.
[o]Also at Università di Napoli Parthenope, Napoli, Italy.
[p]Also at Institute of Particle Physics (IPP), Canada.
[q]Also at Department of Physics, Bolu Abant Izzet Baysal University, Bolu, Türkiye.
[r]Also at Faculty of Physics, University of Bucharest, Romania.
[s]Also at Borough of Manhattan Community College, City University of New York, New York, New York, USA.
[t]Also at National Institute of Physics, University of the Philippines Diliman (Philippines), Quezon City, Philippines.
[u]Also at TRIUMF, Vancouver, British Columbia, Canada.
[v]Also at Universita degli Studi Link, Roma, Italy.
[w]Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
[x]Also at University and INFN Torino, Torino, Italy.
[y]Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
[z]Also at Henan University, Kaifeng, China.
[aa]Also at Yeditepe University, Physics Department, Istanbul, Türkiye.
[bb]Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
[cc]Also at CERN, Geneva, Switzerland.
[dd]Also at Manhattan College, New York, New York, USA.
[ee]Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki, Greece.
[ff]Also at Hellenic Open University, Patras, Greece.
[gg]Also at Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China.
[hh]Also at Department of Physics, Stellenbosch University, South Africa.
[ii]Also at School of Physics, University of the Witwatersrand, Johannesburg, South Africa.
[jj]Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel.
[kk]Also at University of Colorado Boulder, Department of Physics, Colorado, Boulder, USA.
[ll]Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
[mm]Also at Centre of Physics of the Universities of Minho and Porto (CF-UM-UP), Minho, Portugal.
[nn]Also at Indian Institute of Technology (IIT), Jodhpur, India.
[oo]Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
[pp]Also at Washington College, Chestertown, Maryland, USA.
[qq]Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[rr]Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco.
[ss]Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia.
[tt]Also at Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago, Chile.
[uu]Also at University of Chinese Academy of Sciences (UCAS), Beijing, China.